Pressure, Temperature, and Recession Measurements in Extreme Environments

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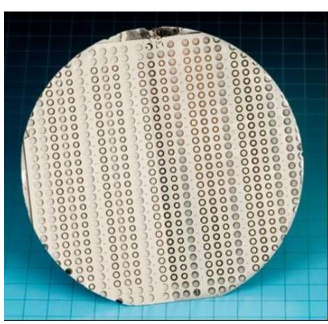
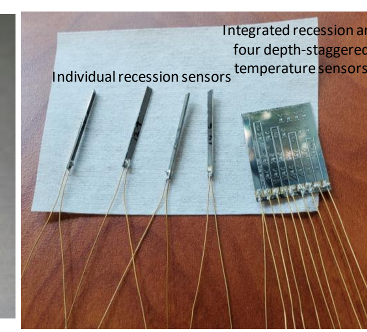


4” SiC wafer with pressure sensors

Swagelok assembled SiC Sensors

Through bore assembled SiC Sensors

NPT assembled SiC Sensors



Recession sensors

Outline

- Application Drivers
- Why SiC for High Temperature Sensing?
- Technical/Technological Challenges
- SiC Pressure Sensor Characterization
- Field Validation
- Recession Sensor Characterization
- Conclusion

Application Drivers

Turbine Engines

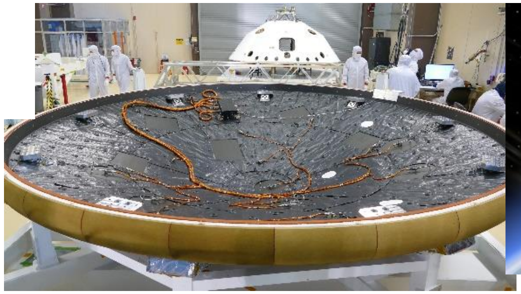
- Thermoacoustic instabilities
- Active combustion control
- Exhaust noise emission

X-43A Scramjet with supersonic Combustion ramjet engine

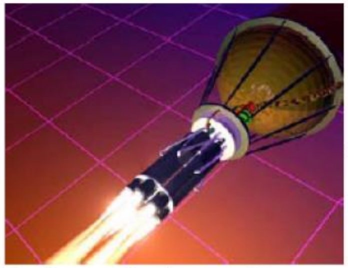
- Combustion instabilities
- Mode Transition Unstart

Venus

- 460 C
- Aggressive chemistry
- Atmospheric pressure (93 Earth atm.)

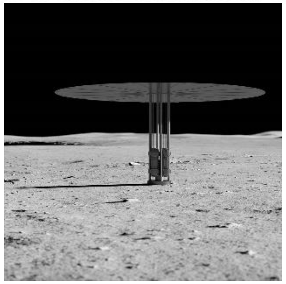


Recession sensors for Thermal Protection Systems



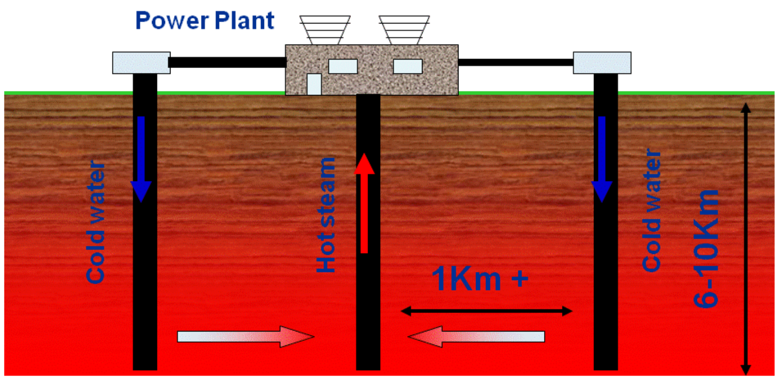
Pulse detonation engine

Pressure pulse/shock quantification



Instrumentation for Advanced Micro Nuclear Reactors

Man Made Geothermal Systems

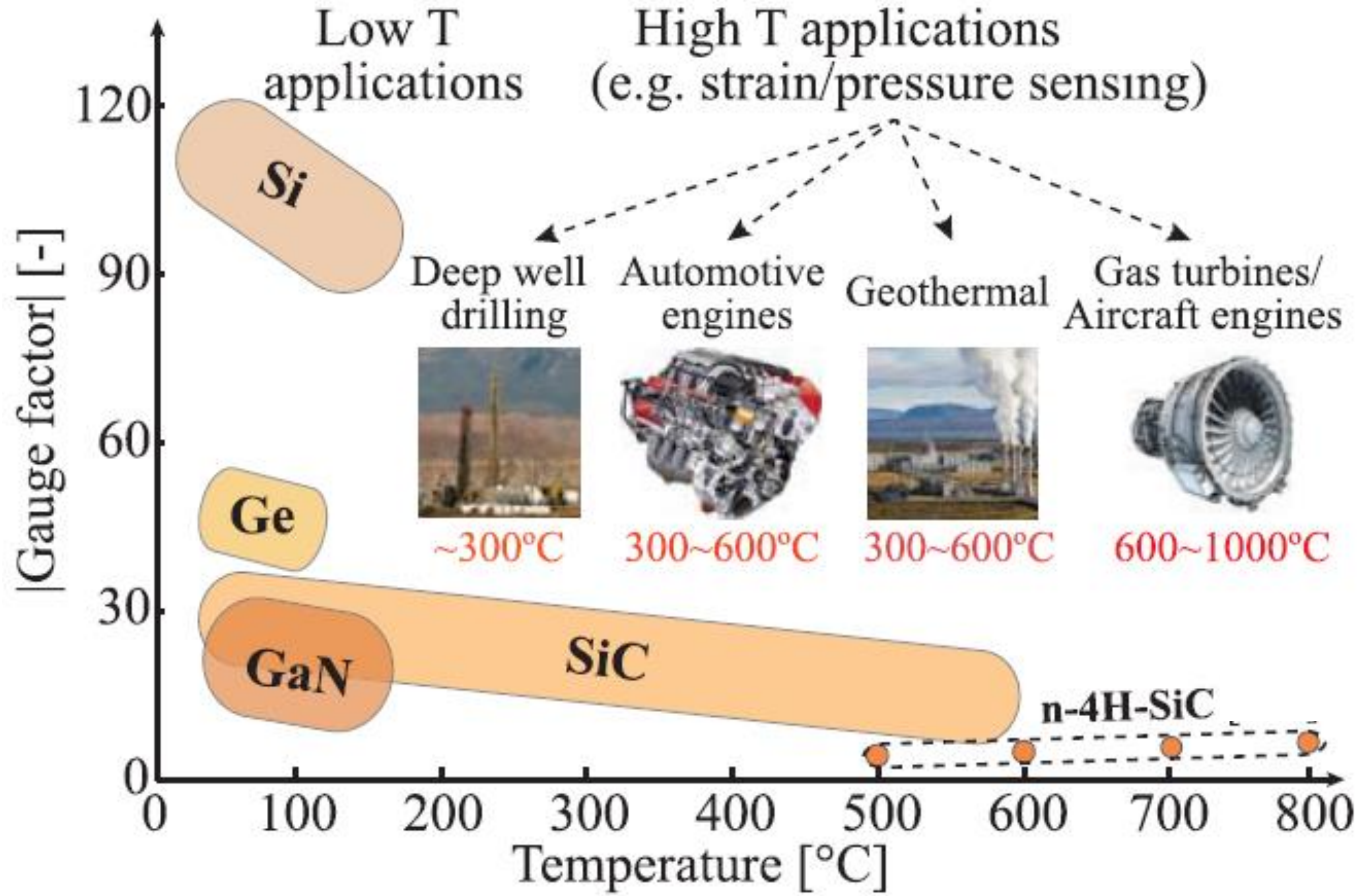


- The Earth is hot. At depths of 6 to 8Km temperatures exceed 200C
- Geothermal tools require electronics to operate from 140 – 325C
- The heat is mined by water flow from injectors to the producer via hydraulic enhanced fractures in the rock.

Why SiC for High Temperature Sensing?

Properties	SiC	Si	Diamond	GaN
Energy gap (eV)	2.3 (3C-SiC) to 3.4 (2H-SiC)	1.12	5.5	3.4
Breakdown voltage (V/cm)	4×10^6	3 to 6×10^5	10×10^6	3×10^6
Electron mobility (cm^2/Vs)	1000	1500	2200	900
Hole mobility (cm^2/Vs)	40 to 100	100 to 500	1600	150
Young's modulus (GPa)	300 to 500	130 to 180	1000	200 to 300
Melting point (°C)	2830*	1410	1400**	2400
Thermal conductivity ($Wcm^{-1}K^{-1}$)	5	1.5	20	1.3
Chemical Inertness	Excellent	Poor	Good but burn	Good
MEMS compatibility	Good	Excellent	Poor	Fair
Availability/Cost	Fair to good	Excellent	Poor	Fair

Piezoresistive Sensors in Common Semiconductors



Stable metal contacts and packaging become more challenging

Hoang-Phuong Phan et al., "The Piezoresistive Effect of SiC for MEMS Sensors at High Temperatures: A Review," JOURNAL OF MICROELECTROMECHANICAL SYSTEMS, VOL. 24, NO. 6, DECEMBER 2015.

Technological Challenges

- Thermomechanical induced stress in package
- Reaction kinetics at contact metallization to device

Failure mechanisms:

- Cracking due to CTE mismatch;
- Die attach delamination;
- Wire bond weakening/detaching due to:
  - inter-metallic diffusion;
  - low temperature eutectic formation;
  - vibration-driven fatigue;
- Unstable electrical contact resistance.

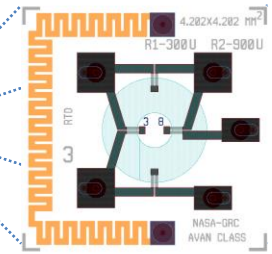
Electrical and Mechanical Failure

Integrated Pressure/Temperature Sensor for 800 ºC Operation

Integrated Pressure/Temp Sensors at 800 °C without Cooling

Accurate Pressure/Temp Relationship, Real-time Temperature Compensation and Voltage-Pressure Conversion.

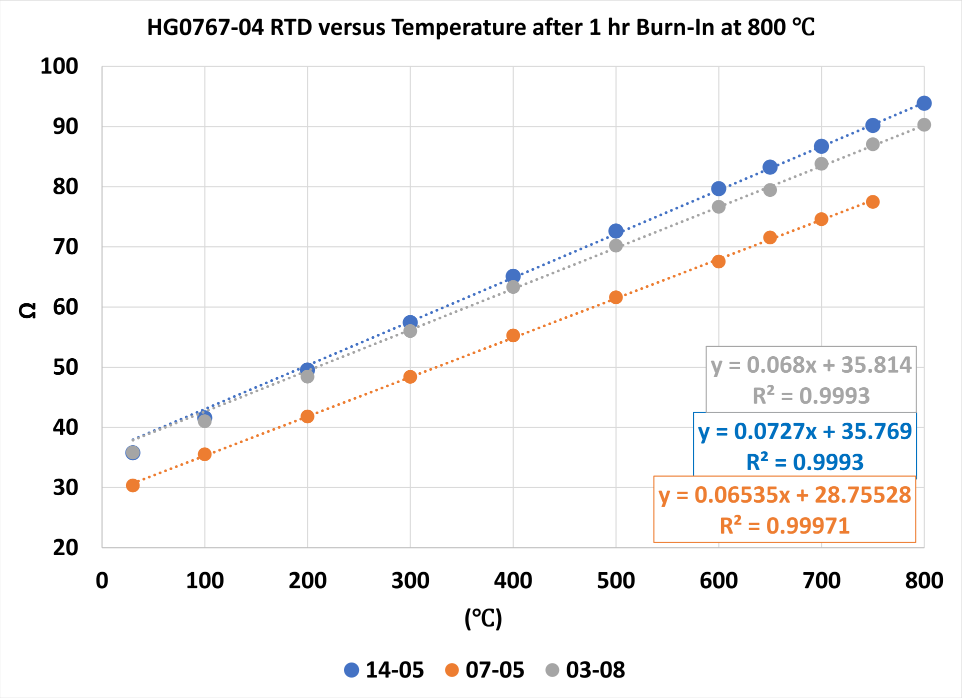
Full-bandwidth Capture of Pressure Transient due to Direct Interaction with Flow-Field at High Temperature.

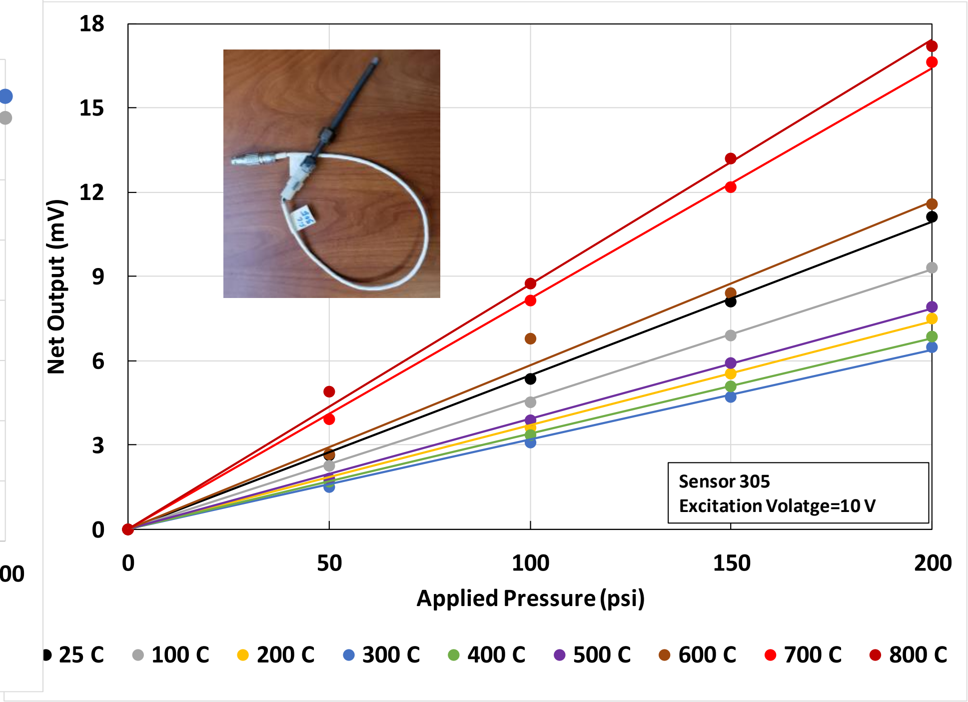


Sensor chip inside

Unique Characteristic: No wire bond Direct Chip Attach

SiC Pressure Sensor Operation at 800 °C

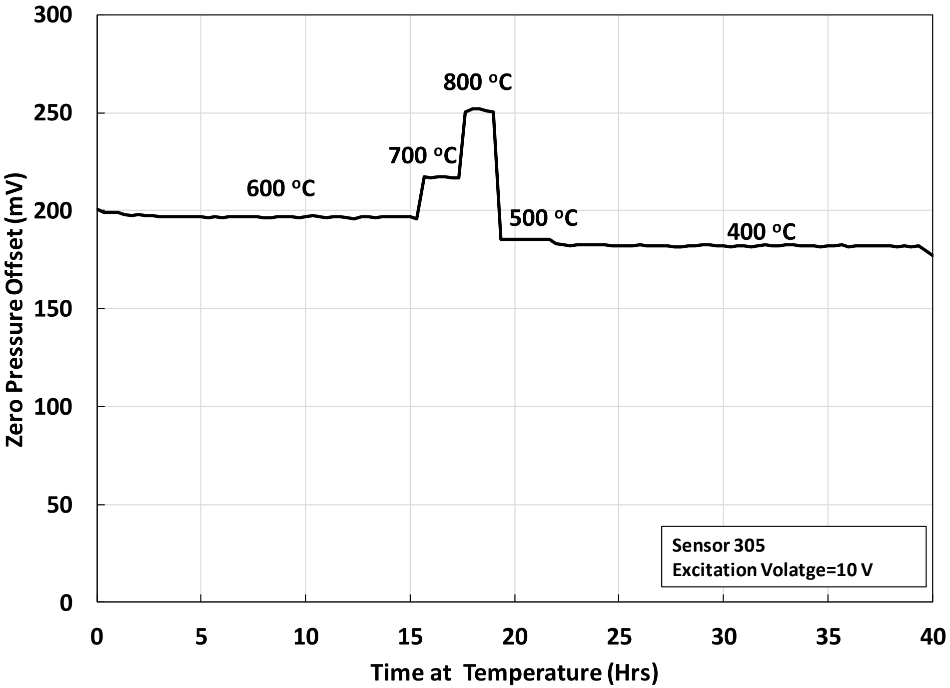


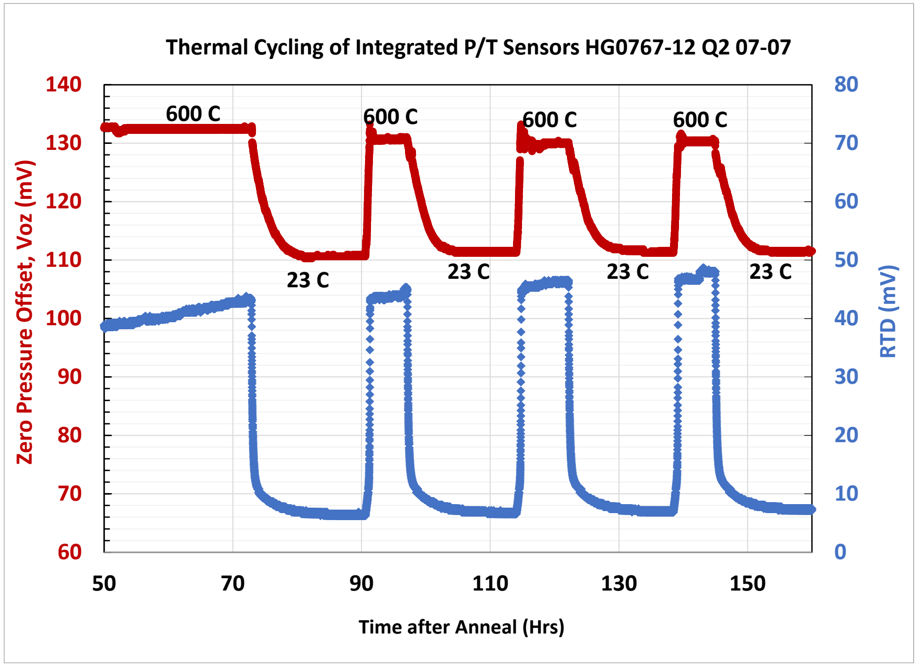


Temperature Sensors

Pressure Sensor

Thermal Cycling Characteristics

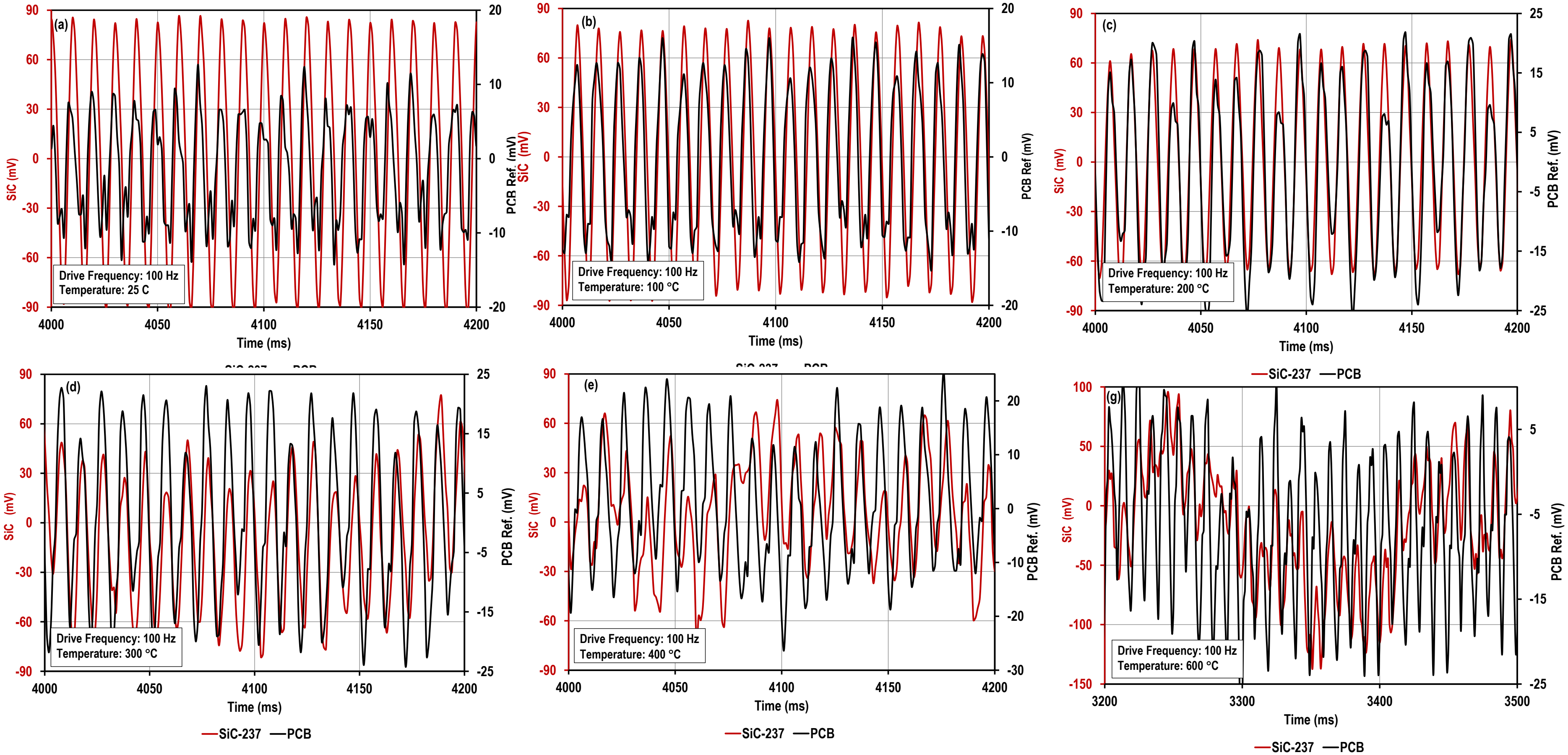




- ***Rise-time spikes due to oven over temperature excursion***
- ***Temperature sensor requires further burn-in to stabilize***

Okojie et al., The International Conference on Solid-State Sensors, Actuators and MicrosystemsTransducers 2019 - EUROSENSORS XXXIII Berlin, GERMANY, 23-27 June 2019

Dynamic Characterization-Time Domain

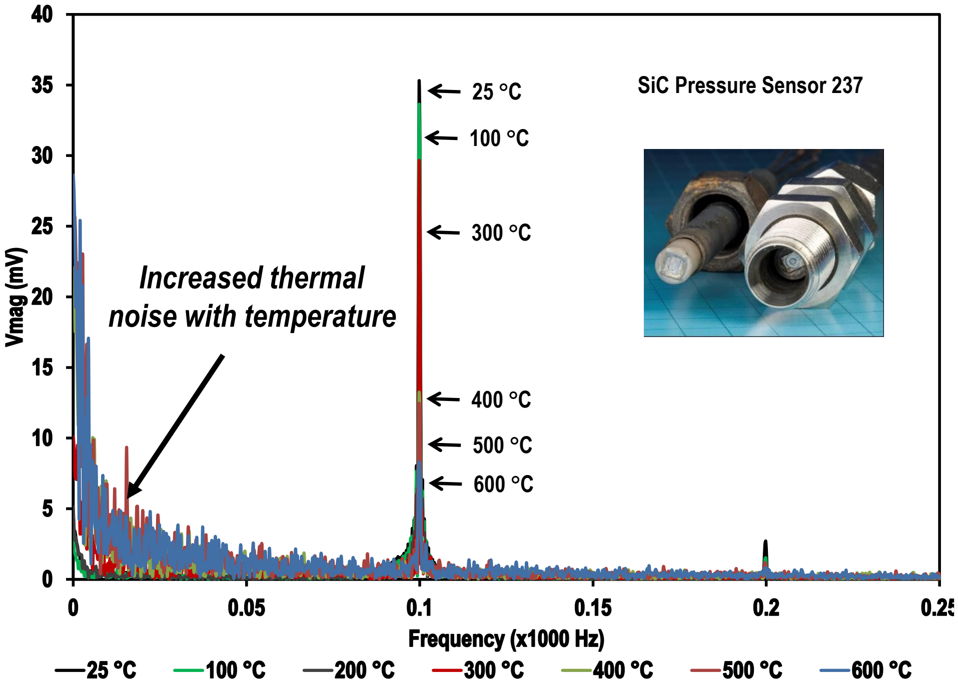


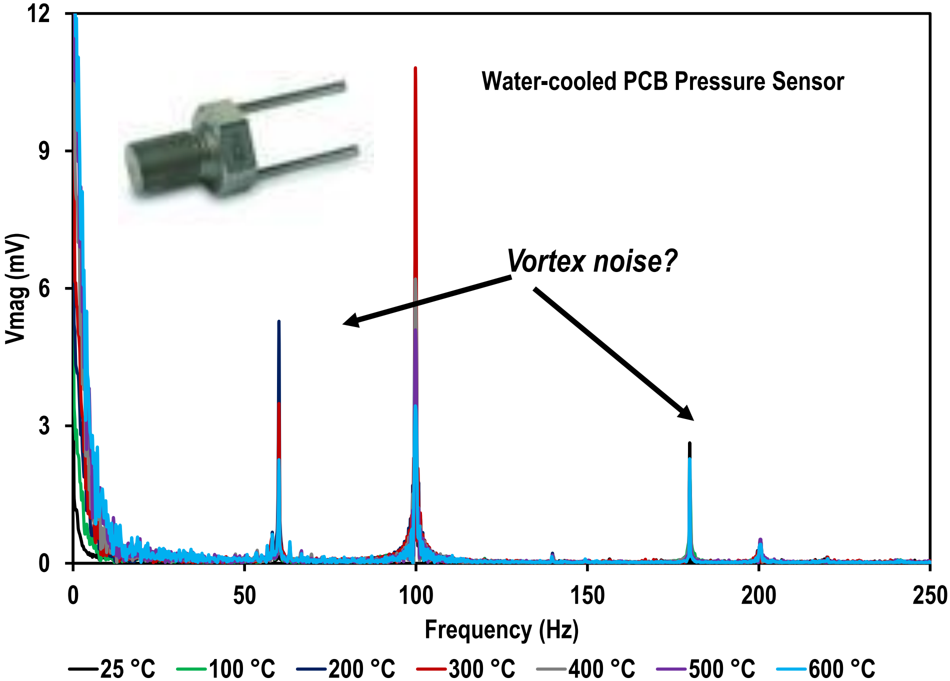
Brief time history of the static SiC and dynamic piezoceramic pressure sensors in response to 100 Hz pressure modulation. Gain=100; Excitation voltage=10 V.

Equivalent Δp=(Dynamic Output/Gain)/[Pressure Sensitivity (T)*Input Voltage]
Δp (Avg)~1.88 psi

Okojie et al., International Conference on High Temperature Electronics (HiTEC), May 13-15, 2014, Albuquerque, NM USA

Dynamic Characterization-Frequency Domain



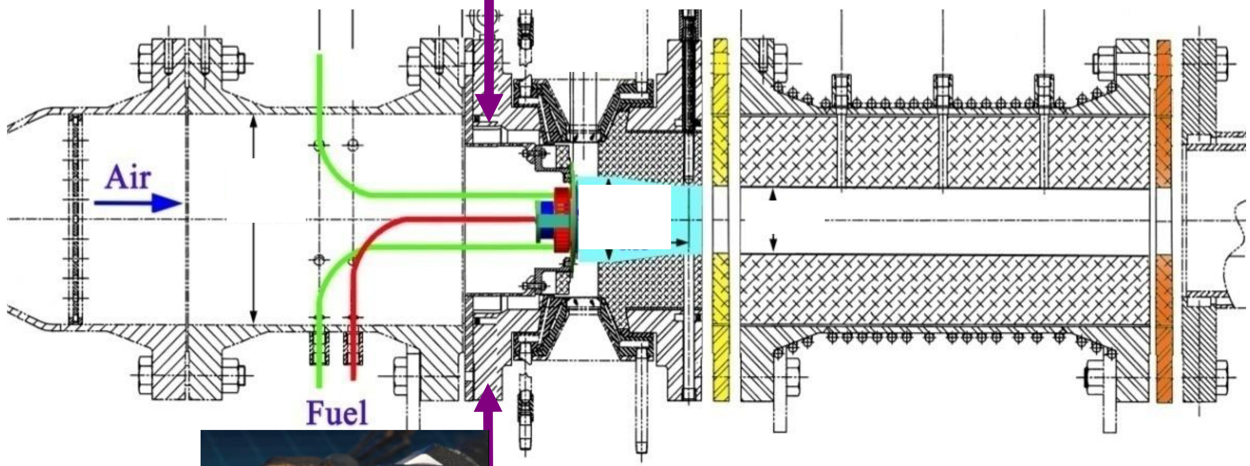


Amplitude magnitude response of the static SiC pressure sensor and the water-cooled dynamic piezoceramic pressure sensor at 100 Hz pressure modulation.

Okojie et al., International Conference on High Temperature Electronics (HiTEC), May 13-15, 2014, Albuquerque, NM USA

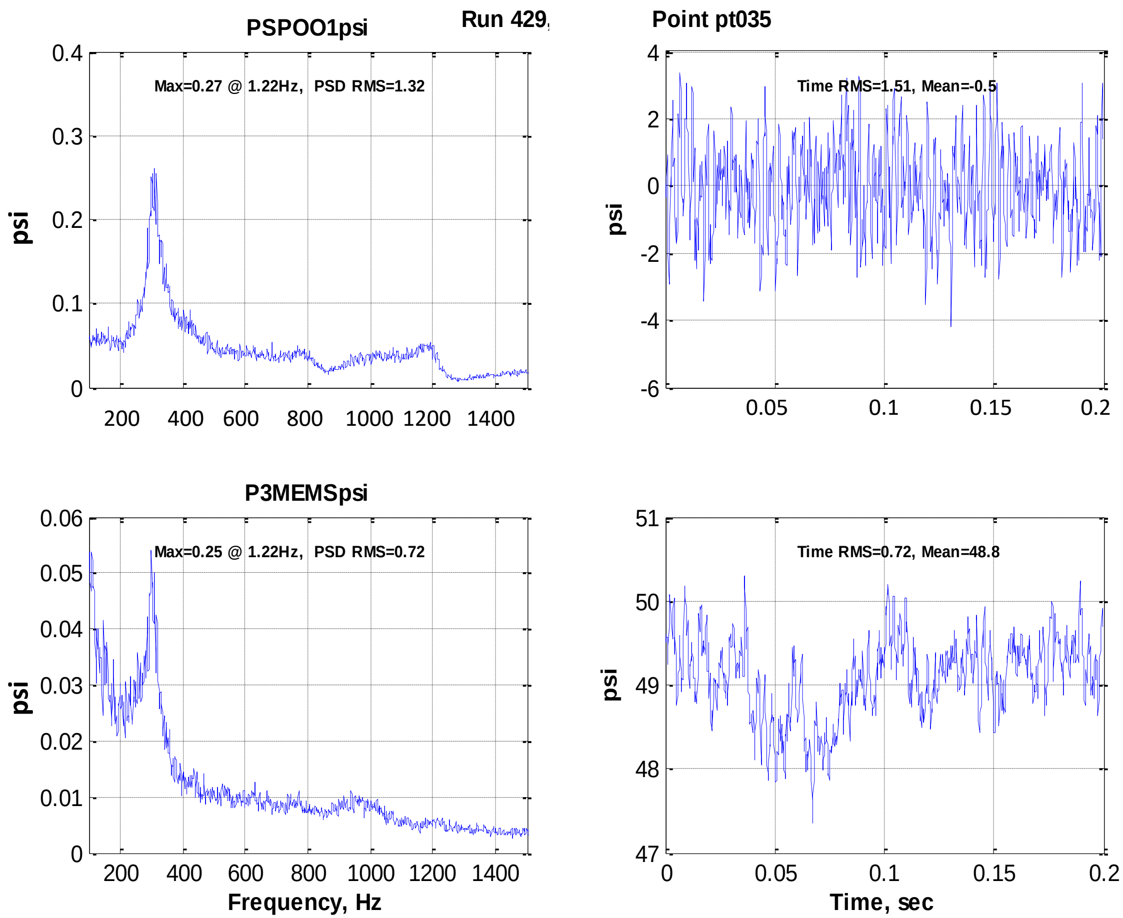
Field Validation: Combustor Rig Test

PCB dynamic pressure transducers mounted on semi-infinite line



Flush mounted SiC dynamic pressure transducer

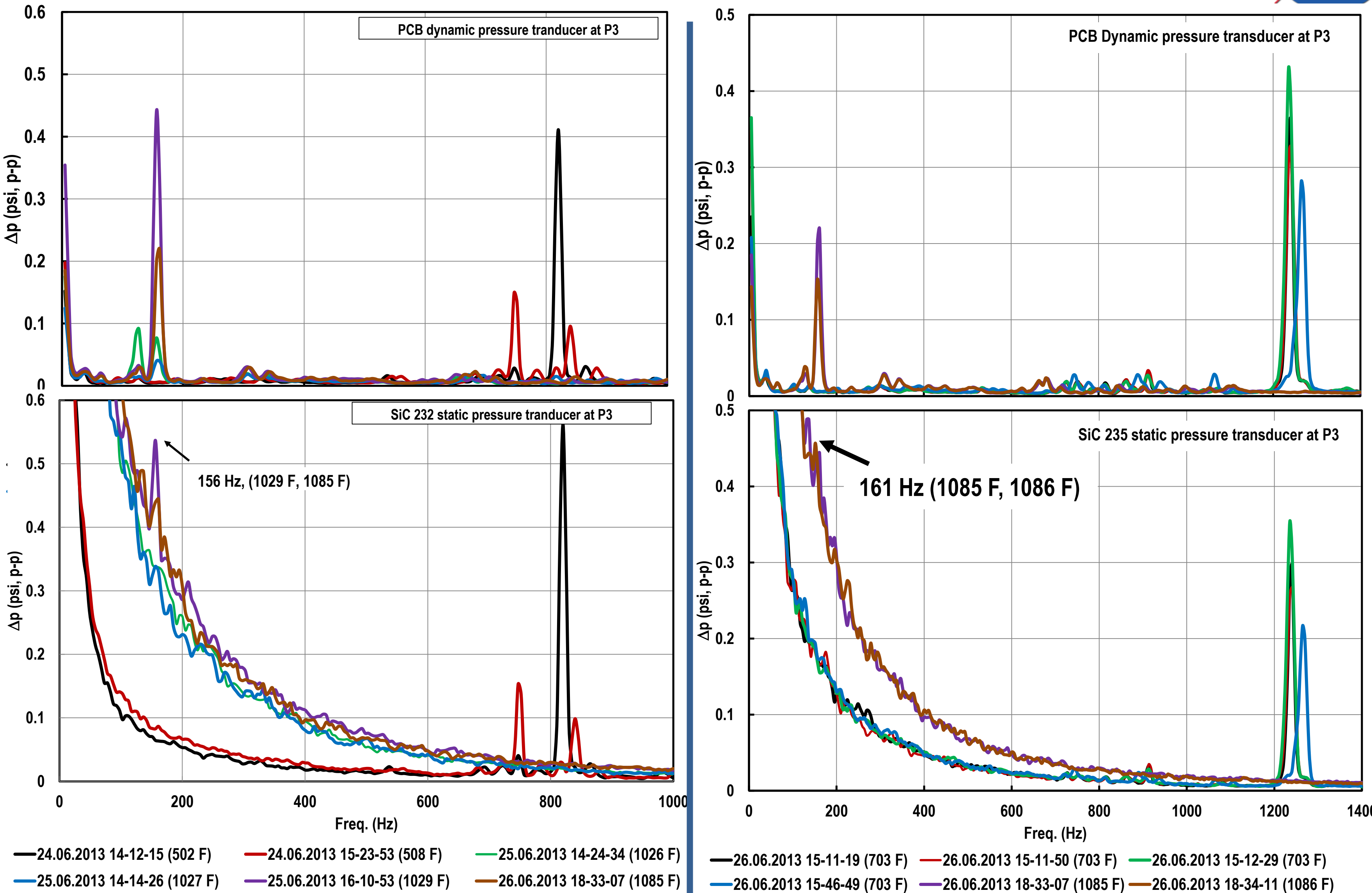
Field Validation: Combustor Rig Test-1



Amplitude magnitude (left column) and brief time history (right column) for the piezoelectric pressure transducer and the SiC pressure transducer shows the detection of thermo-acoustic instability at 310 Hz by both devices.

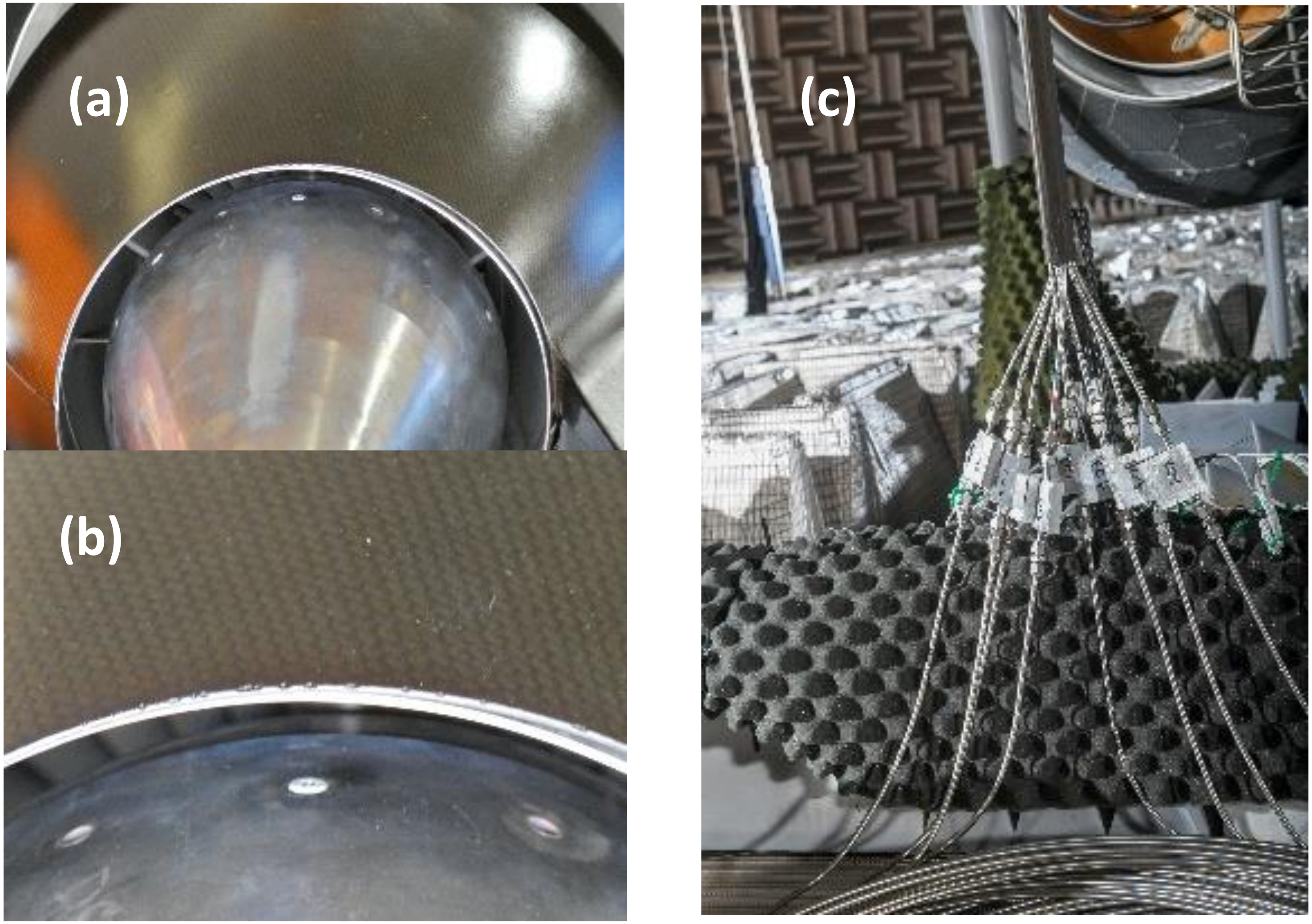
The 13th International Conference on Solid-State Sensors, Actuators and Microsystems, Seoul, Korea, June 5-9, 2005

Field Validation: Combustor Rig Tests 2 and 3



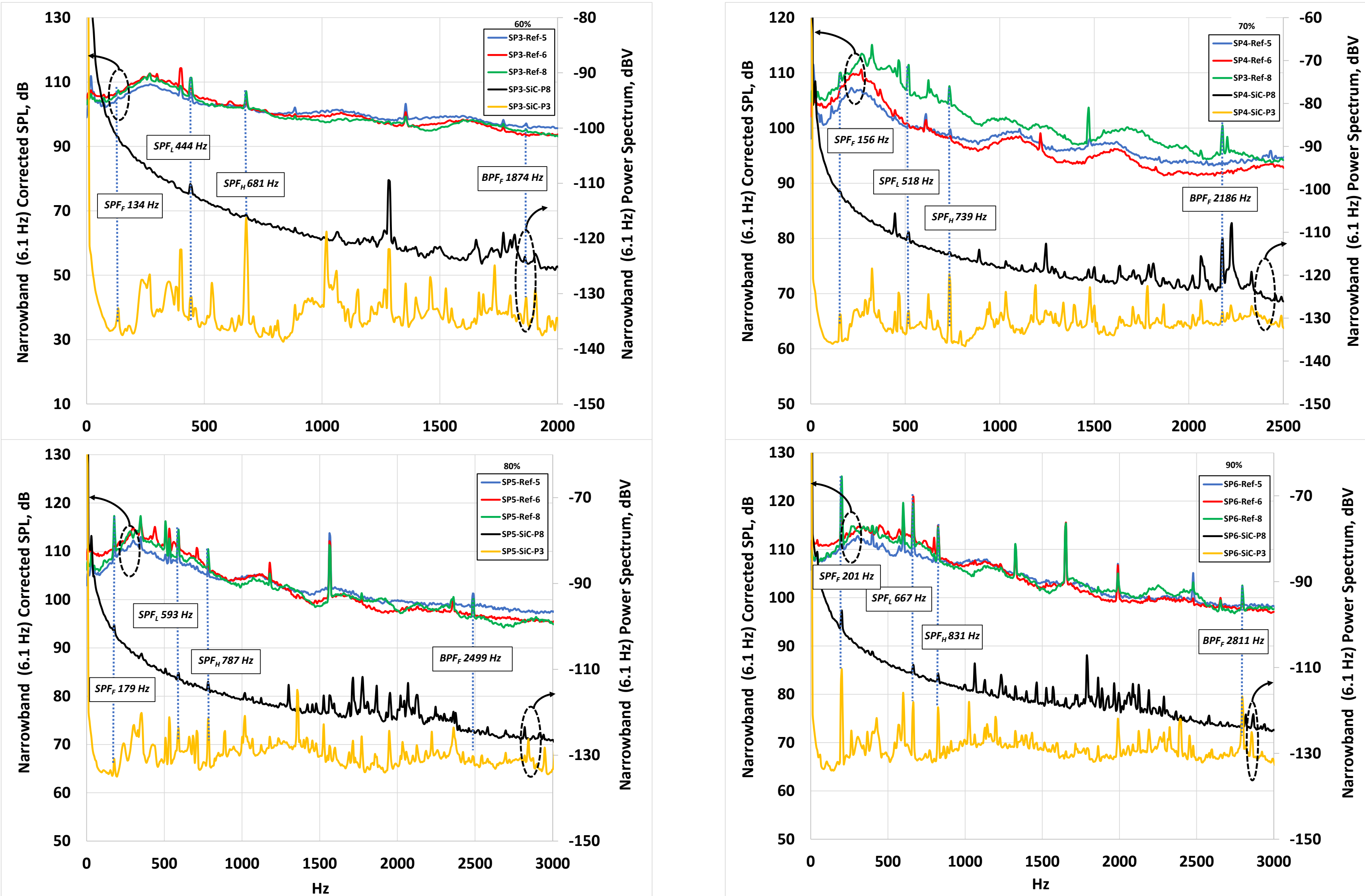
Okojie et al., International Conference on High Temperature Electronics (HiTEC), May 13-15, 2014, Albuquerque, NM USA

Jet Engine Test: Flush-Mounted Versus Infinite Tube Probe



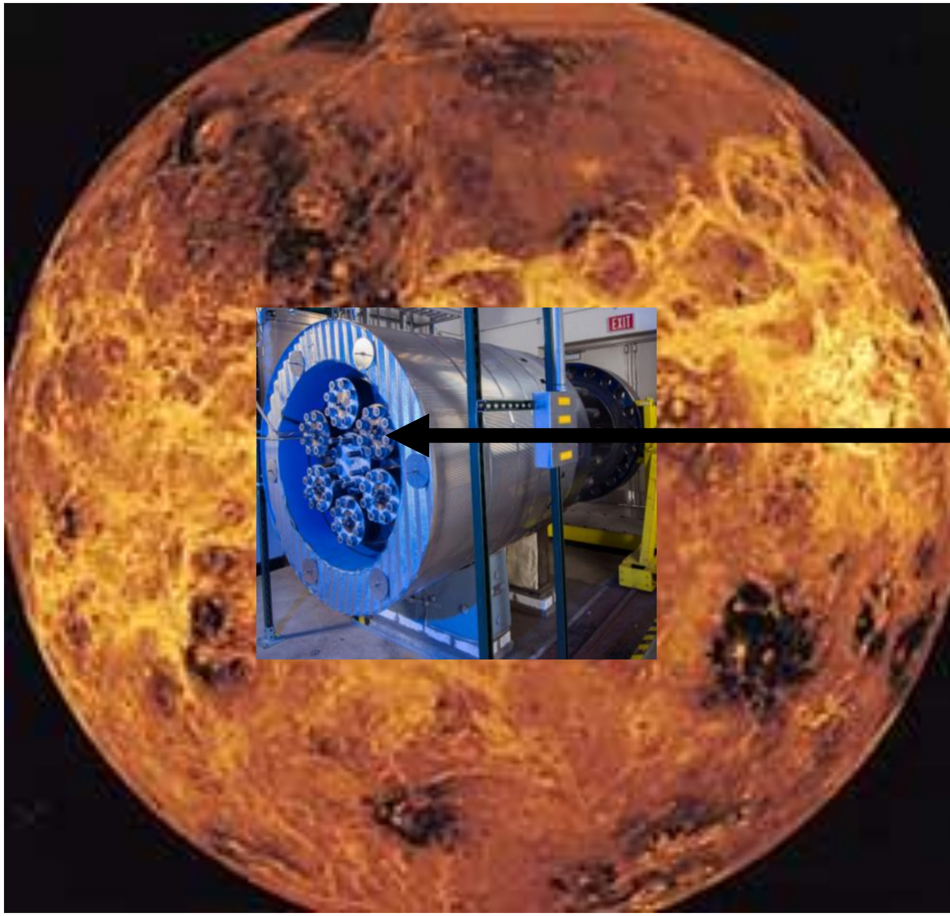
Core exhaust nozzle of NASA DGEN experimental engine showing circumferentially placed pressure ports with open ITP hole terminations, b) flush-mounted SiC pressure sensor between two open ITP holes, and c) benchmark pressure sensors attached to ITPs external to the engine.

Flush-Mounted Versus Infinite Tube Probe (*Engine Test Results*)



Good agreement between flush-mounted SiC pressure sensors and ITP-mounted commercial pressure sensor.

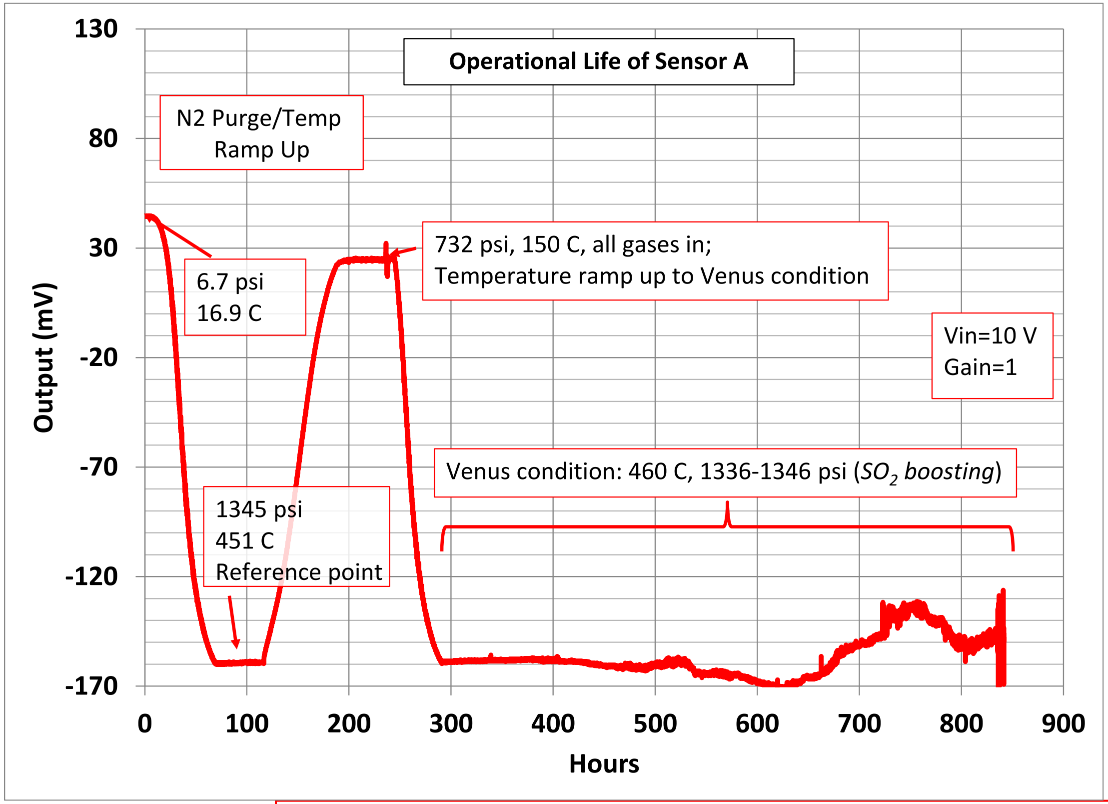
Test in Simulated Venus Environment



NASA GRC Extreme Environment Rig (GEER)

Temperature: 460 C
Pressure: 1356 psia
Chemistry: “Venus atmosphere” 96.5% CO_2, 3.5% N_2, 180 ppm SO_2, 12 ppm CO, 51 ppm OCS, 2 ppm H_2S, 0.5 ppm HCl, 2.5 ppb
HF Range: SO_2 concentration range 100-200 ppm

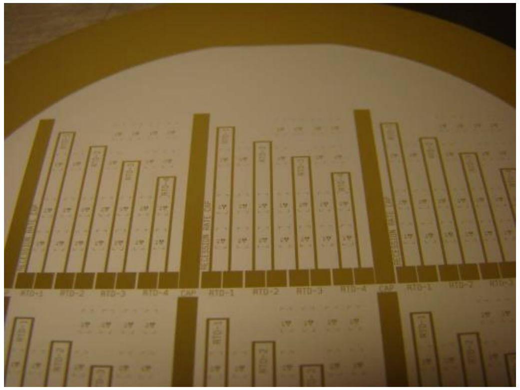
SiC Pressure Sensor Venus Life in GEER

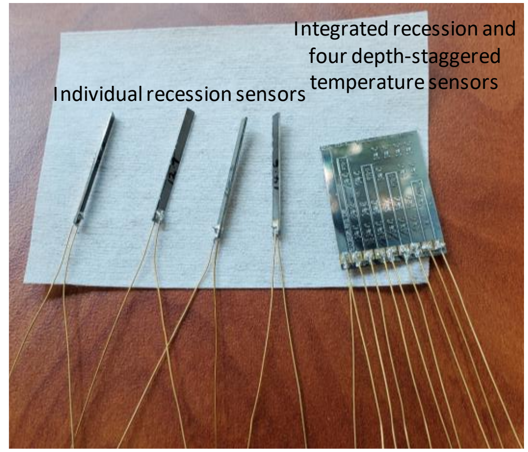


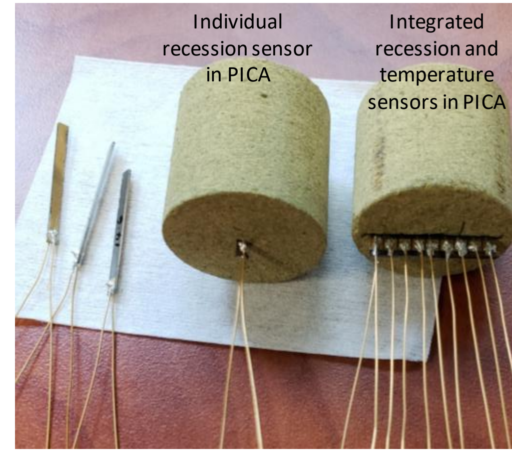
- Sensor reliably operational for ~12 earth days
- Sensor survived 60 earth days
- No mechanical damage
- Reaction chemistry on exposed wires caused failure

Okojie, 2018 International Planetary Probe Workshop Boulder, Colorado

Minimally Intrusive Integrated Recession and Temperature Sensors



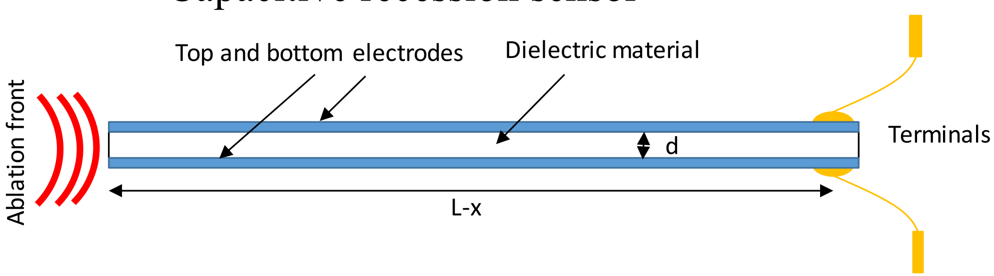




- **Batch fabrication provides uniform measurement**
- **Speeds up production**
- **Reduces costs and reduces human error during sensor placement.**

- **Minimally intrusive insertion into the TPS heatshield.**
- **Large area distribution of sensors leads to improved health monitoring due to high fidelity.**
- **Eliminates need for plugs and inserted directly into the heatshield fore body at point of TPS manufacture.**

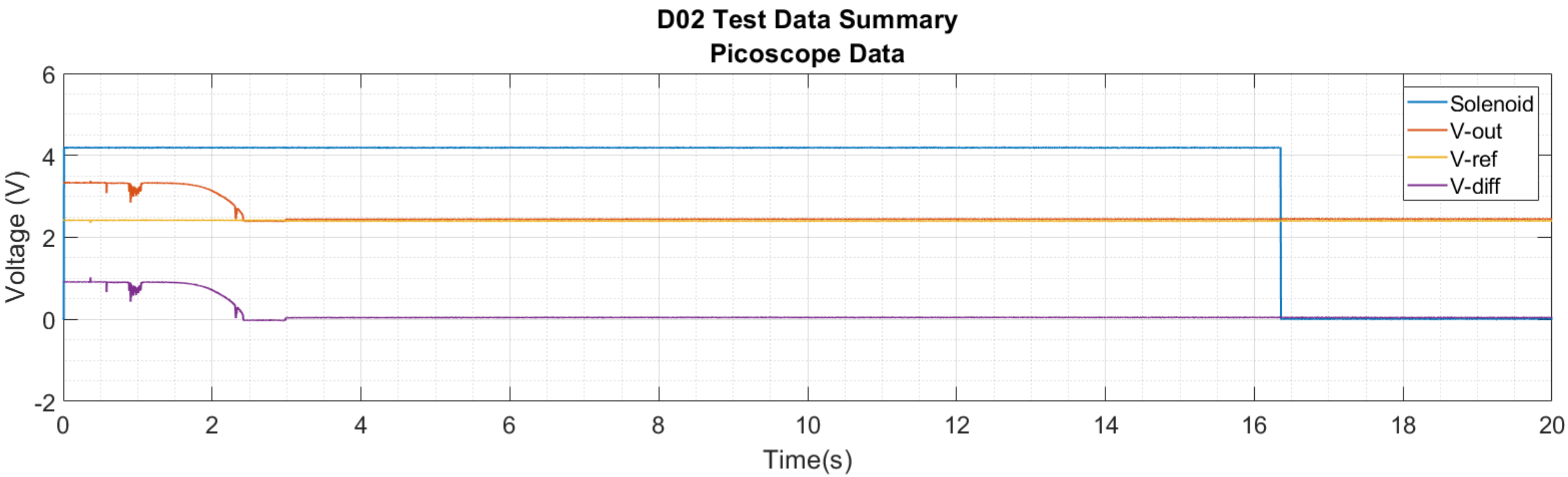
Capacitive recession sensor

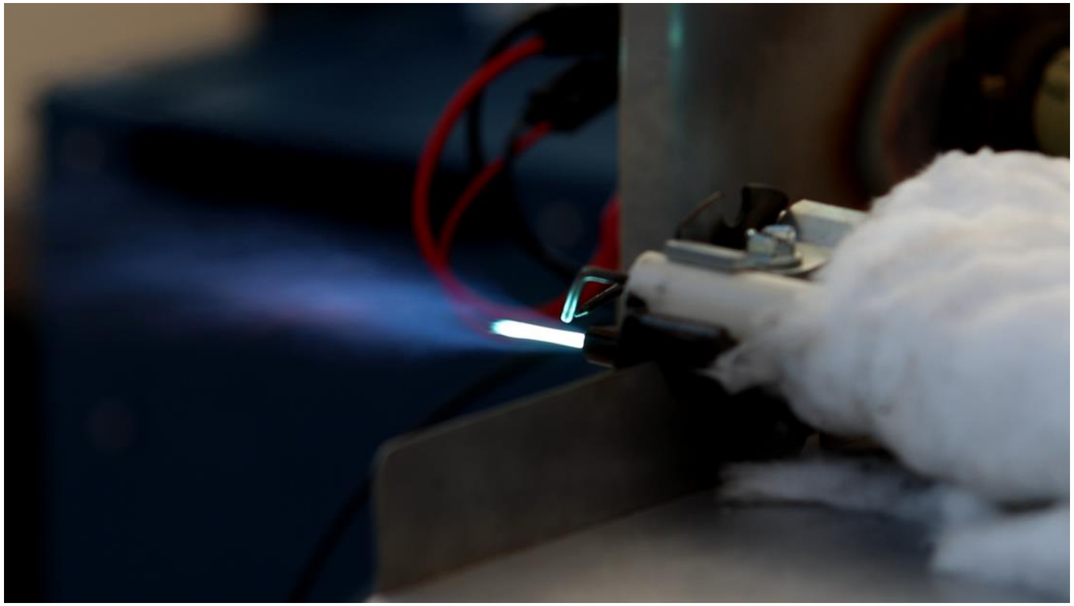


$$C = \frac{\varepsilon[W(L-x)]}{d}$$

Provides real-time monitoring recession due to ablation, attrition, wear, etc.

Recession Sensor Test Results





Voltage output converted to corresponding material loss

Conclusion

- ✓ Successfully developed SiC piezoresistive pressure sensors capable of operating up to 600 ^{o}C for hundreds of hours, and short duration
- ✓ The successful development was the result of years of efforts to overcome the problems of
  - increasing voltage offset drifts with increasing temperature that renders sensors useless.
  - Thermo-mechanically induced failures due to the earlier application of conventional packaging
- ✓ Thermally stable ohmic contacts to SiC resulted in solving the drift problem
- ✓ Introduction of MEMS DCA packaging solved the thermo-mechanical failures
- ✓ Because of this work, it is now possible to apply the SiC pressure sensors for longer duration engine ground tests and potential short duration flight tests in high temperature regimes.
- ✓ First generation capacitive recession sensors demonstrated.
- ✓ Applications include real time monitoring of ablation, abrasion, attrition, and wear.